



Nagai, Y., Nishitani, N., Yasuda, M., Ueda, Y., Fukui, Y., Andoh, C., Shirakawa, H., Nakagawa, T., Inoue, K., Nagayasu, K., Kasparov, S., Nakamura, K., & Kaneko, S. (2019). Identification of neuron-type specific promoters in monkey genome and their functional validation in mice. *Biochemical and Biophysical Research Communications*, 518(4), 619-624. <https://doi.org/10.1016/j.bbrc.2019.08.101>

Peer reviewed version

License (if available):
CC BY-NC-ND

Link to published version (if available):
[10.1016/j.bbrc.2019.08.101](https://doi.org/10.1016/j.bbrc.2019.08.101)

[Link to publication record in Explore Bristol Research](#)
PDF-document

This is the author accepted manuscript (AAM). The final published version (version of record) is available online via Elsevier at <https://www.sciencedirect.com/science/article/pii/S0006291X19316249> . Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

Identification of neuron-type specific promoters in monkey genome and their functional validation in mice

Yuma Nagai^{1,*}, Naoya Nishitani^{1,2,*}, Masaharu Yasuda³, Yasumasa Ueda³, Yuto Fukui¹, Chihiro Andoh¹, Hisashi Shirakawa¹, Takayuki Nakagawa⁴, Ken-ichi Inoue^{5,6}, Kazuki Nagayasu¹, Sergey Kasparov⁷, Kae Nakamura³, Shuji Kaneko¹

1: Department of Molecular Pharmacology, Graduate School of Pharmaceutical Sciences, Kyoto University, 46-29 Yoshida-Shimoadachi-cho, Sakyo-ku, Kyoto 606-8501, Japan

2: Department of Neuropharmacology, Faculty of Medicine and Graduate School of Medicine, Hokkaido University, N15 W7 Kita-ku, Sapporo 060-8638, Japan

3: Department of Physiology, Kansai Medical University, 2-5-1 Shinmachi, Hirakata-city, Osaka 573-1010, Japan

4: Department of Clinical Pharmacology and Therapeutics, Kyoto University Hospital, 54 Shogoin Kawahara-cho, Sakyo-ku, Kyoto 606-8507, Japan

5: Systems Neuroscience Section, Department of Neuroscience, Primate Research Institute, Kyoto University, Inuyama, Aichi 484-8506, Japan

6: PRESTO, Japan Science and Technology Agency, Kawaguchi, Saitama, 332-0012, Japan

7: School of Physiology Pharmacology and Neuroscience, University of Bristol, Bristol, UK

*: *These authors contributed equally to this work*

Corresponding authors:

Dr. Kazuki Nagayasu (Co-corresponding author for communication
with editorial office)

Department of Molecular Pharmacology, Graduate School of
Pharmaceutical Sciences, Kyoto University,
46-29 Yoshida-Shimoadachi-cho, Sakyo-ku, Kyoto 606-8501, Japan
Tel: +81-75-753-4548; Fax: +81-75-753-4548.

E-mail: nagayasu@pharm.kyoto-u.ac.jp

Prof. Shuji Kaneko (Co-corresponding author)

Department of Molecular Pharmacology, Graduate School of
Pharmaceutical Sciences, Kyoto University,
46-29 Yoshida-Shimoadachi-cho, Sakyo-ku, Kyoto 606-8501, Japan
Tel: +81-75-753-4541; Fax: +81-75-753-4542.

E-mail: skaneko@pharm.kyoto-u.ac.jp

Running title: Neuron-type specific promoters from monkey

Abstract

Viral gene delivery is one of the most versatile experimental techniques for elucidating the mechanisms underlying brain dysfunction, such as mental and neurodegenerative disorders. Due to the complexity of the brain, expression of genetic tools, such as channelrhodopsin and calcium sensors, often has to be restricted to a specified cell type within a circuit implicated in these disorders. Only a handful of promoters targeting neuronal subtypes are currently used for viral gene delivery. Many of them use human genomic elements although used typically in mice or rats. Here, we isolated conserved promoter regions of several subtype-specific genes from the macaque genome and investigated their functionality in the mouse brain when used within lentiviral vectors (LVVs). Immunohistochemical analysis revealed that transgene expression induced by the promoter sequences for somatostatin (SST), cholecystokinin (CCK), parvalbumin (PV), serotonin transporter (SERT), vesicular acetylcholine transporter (vAChT), substance P (SP) and proenkephalin (PENK) was largely colocalized with specific marker for the targeted neuronal populations. Moreover, by combining these results with in silico predictions of transcription factor binding to the isolated sequences, we identified transcription factors possibly underlying cell-type specificity. These findings lay a foundation for the expansion of the current toolbox of promoters suitable for elucidating these neuronal phenotypes.

1 Introduction

2 Abnormal neuronal activity causes the symptoms of a variety of neuropsychiatric
3 disorders, including Alzheimer's disease, Parkinson's disease, autism, schizophrenia, and
4 major depression¹⁻⁵. Genetic tools such as optogenetic or chemogenetic actuators and
5 sensors for intracellular molecules⁶⁻¹⁰, are among the most versatile experimental
6 techniques for elucidating the mechanisms underlying these disorders. Indeed,
7 application of these tools in rodents has revealed the neural mechanisms contributing to
8 these disorders¹¹⁻¹⁵. At the same time, monkeys have ability to perform complex tasks
9 due to their high intelligence. Moreover, the brain structures of humans and monkeys are
10 very similar, especially the cerebral cortex, which plays a key role in memory, learning,
11 emotion, and cognition. Some brain nuclei, such as the pulvinar nucleus, is present only
12 in primates but not in rodents. Furthermore, genome sequence of monkeys is highly
13 homologous to that of humans^{17, 18}. Therefore, the application of neuron type-specific
14 genetic tools to monkeys should not only help to extrapolate observations made in rodents
15 to humans, but also provides deep insights into the mechanisms of brain function in health
16 and disease.

17 It is necessary to reach sufficient level of expression of genetic tools in a specific
18 population of neurons for manipulation and monitoring of its neural activity¹⁹⁻²³. In
19 rodents, especially in mice, this has been often achieved by utilizing Cre-driver lines and
20 Cre-dependent adeno-associated viral vectors^{24, 25}. On the other hand, in other species
21 where a Cre-driver line is not readily available, such as in monkeys, viral vectors with
22 cell-type specific promoters are indispensable for achieving cell-type specific transgene

1 expression.

2 In this context, human synapsin (hSyn) and mouse calmodulin kinase II α (mCaMKII α)
3 promoters were used to target neurons in monkeys²⁶⁻³¹. Recently, Stauffer et al. have
4 demonstrated that a short tyrosine hydroxylase (TH) promoter can transduce dopamine
5 neurons with high neuron-type specificity, and have optogenetically manipulated their
6 activity³². El-Shamayleh et al. have shown that an L7 promoter allows specific expression
7 in Purkinje cells in the cerebellum and is sufficiently active for optogenetic manipulation
8 of these cells in monkeys³³. Interestingly, both of these reports employed promoter
9 sequences that were isolated from rodents and were effective in monkeys. Binding motifs
10 of transcription factors, which underlie cell-type specific promoter activity, are highly
11 conserved across species³⁴. Moreover, a systematic comparison of mammalian genomes
12 has revealed that promoter regions are evolutionarily conserved compared to intronic
13 regions or the whole genome³⁵. These results indicate that upstream regions of protein
14 coding sequences are good candidates for development of cell-type specific promoters
15 active across species. Indeed, we have shown that lentiviral vectors (LVVs) with a 2-kb
16 rodent tryptophan hydroxylase 2 (TPH2) promoters, which is well conserved across
17 species, are capable of inducing sufficient expression of optogenetic tools specific to
18 rodent serotonergic neurons for manipulation of these neurons *in vivo*²³. These
19 considerations prompted us to screen the activity of evolutionarily conserved promoter
20 sequences from monkeys in the mouse.

21 In this study, we isolated promoter candidates for several well-established neuronal
22 markers³⁶⁻⁴⁰, somatostatin (SST), cholecystokinin (CCK), parvalbumin (PV), serotonin

transporter (SERT), choline acetyltransferase (ChAT), substance P (SP), and enkephalin (PENK), from the genome of crab-eating macaques (*Macaca fascicularis*) through comparative analysis of upstream regions between mice and monkeys. We investigated the promoter activity of the isolated sequences in mice using LVVs^{23,41} and found that several of these promoter candidates were capable of inducing transgene expression in a neuron-type specific manner.

Materials and methods

Animals

Adult male and female C57BL/6J mice (8-16 weeks old; Nihon SLC, Shizuoka, Japan) were used in this study. All animal experiments were performed in accordance with the ethical guidelines of the Kyoto University Animal Experimentation Committee, and were approved by the Kyoto University Animal Experimentation Committee. Mice were housed in groups (no more than 6 mice in an individual cage) with free access to food and water and kept under constant ambient temperature (24 ± 1 °C) and humidity (55 ± 10 %) and a 12-hr light-dark cycle. The sample size was similar to that in previous report²³ and was estimated to be sufficient to determine the specificity of each promoters. Mice were randomly assigned to experimental groups. Blinding was not performed.

Isolation of the upstream sequence of neuronal markers and vector construction

Genomic DNA of crab-eating macaque (*Macaca fascicularis*) was isolated from blood by using QIAamp DNA Blood Minikit (Qiagen, Hilden, Germany). Upstream sequences of

somatostatin (SST), cholecystokinin (CCK), parvalbumin (PV), serotonin transporter (SERT), vesicular acetylcholine transporter (vAChT), substance P (SP) and enkephalin (PENK) were isolated from crab-eating macaque genomic DNA by PCR. PCR was performed with KOD FX Neo (Toyobo, Osaka, Japan) or Q5 DNA polymerase (New England Biolabs, Ipswich, MA, USA). Sequences of primers are shown in Supplementary Table 1. PCR-amplified upstream sequences were digested with *MluI* and *NotI* and ligated into the lentiviral plasmid backbone, pTYF-super-mTPH2-Venus-WPRE²³, which was pre-digested with *MluI* and *NotI*. All ligation reactions were performed with DNA Ligation Kit Mighty Mix (Takara Bio, Otsu, Japan). Transgene Venus⁴² is a variant of eYFP and was used as reporter gene in this study. The structure of resulting constructs was pTYF-5xGal4-binding sequences-promoter-Venus-IRES-Gal4p65-WPRE, thus incorporating the positive enhancer feedback loop^{41, 43}. The plasmids containing the isolated promoters will be deposited to Addgene.

Lentiviral vector production

Production and purification of LVVs were performed as described previously^{23, 44}. Briefly, LVVs were produced by transient cotransfection of Lenti-X 293T cells (Clontech, Mountain View, CA, USA) with a pTYF shuttle vector⁴⁵ (15.5 µg), a packaging vector pNHP (31.2 µg), and a plasmid for envelope protein expression (vesicular stomatitis virus glycoprotein, VSVG, 12.4 µg). After 16-18 hrs of incubation, the supernatant was harvested, and fresh media was added to the culture. After 30 hrs of incubation, the supernatant was collected and mixed with that of the first harvest. The supernatants were

1 filtered through a 0.45- μ m pore PVDF membrane (Millex-HV, Merck Millipore, Billerica,
2 MA, USA) and ultracentrifuged for 2 hr 40 min at 20,000 rpm in an SW-28 rotor
3 (Beckman-Coulter, Brea, CA, USA). The resulting pellet was suspended in phosphate
4 buffered saline (PBS) and stored at -80 °C. The titers of LVVs were measured by p24
5 ELISA kit (R&D systems, Minneapolis, MN, USA), and estimated to be approximately
6 1×10^{10} IU/mL.

7 **Stereotaxic surgery**

9 Stereotaxic surgeries were conducted using a small animal stereotaxic frame (Narishige,
10 Tokyo, Japan) and performed according to the Brain Atlas⁴⁶. The sites of injections were
11 selected based on the known expression pattern of each of the target genes. Mice were
12 anesthetized with sodium pentobarbital (50 mg/kg, i.p., Kyoritsu Seiyaku, Tokyo, Japan).
13 Under pentobarbital anesthesia, all mice were injected with 1 μ L of LVV. The following
14 coordinates (in mm) were used for stereotactic injections: SST and CCK, cingulate cortex
15 (AP +0.98 mm, ML 0.3 mm, DV +2.0 mm from bregma) and M2 cortex (AP +0.74 mm,
16 ML 1.0 mm, DV +1.5 mm from bregma); PV, thalamic reticular nucleus (AP -0.70 mm,
17 ML 1.1 mm, DV +4.2 mm from bregma); SERT, dorsal raphe nucleus (AP -4.3 mm, ML
18 1.2 mm, DV +3.6 mm, 20° from bregma); vAChT, lateral dorsal tegmentum (AP -5.02
19 mm, ML 0.5 mm, DV +3.3 mm from bregma); and SP and PENK, striatum (AP +0.38
20 mm, ML 2.0 mm, DV +3.5 mm from bregma).

21 **Immunohistochemistry**

One week after LVV injection, mice were perfused transcardially with PBS and 4% paraformaldehyde (Nacalai Tesque, Kyoto, Japan) in 0.1 M phosphate buffer (pH 7.4) under pentobarbital anesthesia. The brain was removed from the skull, and stored in 15 % sucrose in 0.01 M PBS at 4°C overnight, and 30-μm-thick frozen sections were prepared by freezing microtome (Leica CM3050S; Leica Biosystems, Nussloch, Germany) and stored at -80°C until immunohistochemical processing. For immunohistochemistry, the sections were immersed in 0.25% Triton-X 100 (Nacalai Tesque) for permeabilization and then incubated with each primary antibody under appropriate conditions. Details of the primary antibodies and immunostaining conditions are described in Supplementary Table 2. After washing with PBS, the glass slides were incubated in secondary antibody solution, specifically Alexa Fluor 488- or 594-labeled donkey anti-rabbit, anti-goat, anti-sheep and anti-rat IgG (1:200; Life Technologies, Carlsbad, CA, USA) for 2 hrs at room temperature. After washing with PBS, sections were mounted with Fluoromount Plus (Diagnostic Biosystems, Pleasanton, CA, USA). Immunoreactivity was visualized by confocal microscopy (Fluoview FV10i, Olympus, Tokyo, Japan). In some cases, antigen retrieval by citrate buffer or HistoVT One (Nacalai Tesque) was performed before permeabilization (see Supplementary Table 2).

***In silico* prediction and comparison of transcription factor binding**

An open-access database of transcription factor binding profiles, ConSite⁴⁷, was used for in silico prediction of transcription factor (TF) binding to the sequence. In this method, the program scans the isolated promoter sequences to examine whether a set of TF binds

to each fragment of sequences or not based on a matrix tabulating observed nucleotides in each position of the protein-DNA interface⁴⁷, and calculates the scores which are normalized to 0-100% range. For all isolated sequences, the TF score cutoff was set to 80%.

Data Analysis

Specificity was evaluated by the colocalization of Venus with a canonical reporter gene for each cell type. All values were expressed as mean \pm standard error of mean.

Results

Isolation and functional validation of promoter candidates for SST, CCK, and PV neurons

In the cerebral cortex, there are excitatory and inhibitory neurons. Specific expression using viral vectors in excitatory and inhibitory neurons is often achieved by the CaMKII α promoter and the Dlx promoter, respectively⁴⁸⁻⁵⁰. However, inhibitory neurons are further classified into several subtypes, including somatostatin (SST)-, cholecystokinin (CCK)-, and parvalbumin (PV)-positive neurons. Importantly, short promoters that are active specifically in these subtypes of inhibitory neurons have not yet been identified in any species including mice. First, we identified conserved promoter region upstream of the SST gene through homology analysis of mice and crab-eating macaque using zPicture⁵¹ (Fig. 1A). We found that sequence just upstream of the SST start codon was highly

1 conserved among these species. We produced LVVs bearing this conserved region
2 upstream of Venus (LVV-SST-0.3 kb::Venus). One week after injection of LVV-SST-0.3
3 kb::Venus into the cingulate cortex of mice, the specificity of the promoter candidate was
4 evaluated by immunohistochemical analysis. We found that 93.8 ± 4.1 % of Venus-
5 immunoreactive cells were also SST-immunoreactive (n = 4 mice; Fig.1B, C). This result
6 indicates that this conserved region is active specifically in SST-positive neurons.
7 Similarly, we isolated promoter candidates containing conserved promoter regions
8 upstream of the CCK gene (Fig. 2A). LVVs containing these promoters (LVV-CCK-0.5
9 kb::Venus and LVV-CCK-3.9 kb::Venus) were injected into the cingulate cortex of mice.
10 One week after viral injection, the specificity of the promoters was analyzed
11 immunohistochemically. A large proportion of GFP expression was confined to CCK-
12 immunoreactive cells in animals injected with LVV-CCK-0.5 kb::Venus (colocalization
13 rate 88.0 ± 3.3 %, n = 3 mice; Fig. 2B, C), whereas GFP expression was observed not
14 only in CCK-immunonegative cells but also other cells in animals injected with LVV-
15 CCK-3.9 kb::Venus (colocalization rate 50.9 ± 3.3 %, n = 3 mice; Fig. 2D, E). These
16 results suggest that CCK neuron-specific promoter activity is coded in the proximal
17 region of the upstream region of the CCK gene and addition of a more distal region leads
18 to nonspecific transgene expression. Further, we isolated a conserved promoter region
19 upstream of the PV gene. LVVs bearing two promoter candidates (LVV-PV-0.8 kb::Venus
20 and LVV-PV-1.8 kb::Venus) were injected into the reticular nucleus, because PV-positive
21 neurons are more densely distributed in the reticular nucleus than in the cerebral cortex.
22 Immunohistochemical analysis revealed that 84.0 ± 1.4 % of GFP-immunoreactive cells

also expressed PV in animals injected with LVV-PV-0.8 kb::Venus (n = 3 mice; Fig. 3B, C), whereas 79.3 ± 0.5 % of GFP-immunoreactive cells were immunopositive for PV in animals injected with LVV-PV-1.8 kb::Venus (n = 3 mice; Fig. 3D, E). These results indicate that as little as 0.8 kb upstream region of the PV gene is sufficient for preferential expression in this neuronal subtype.

We investigated whether the isolated promoters induce strong transgene expression so that fluorescence of transgene Venus is detectable without immunohistochemical enhancement. We found that strong Venus fluorescence was induced by LVV-SST-0.3kb::Venus, LVV-CCK-0.5kb::Venus, or LVV-PV-0.8kb::Venus (Supplementary Fig. S1A-C).

Isolation and functional validation of promoter candidates for serotonergic and cholinergic neurons

Serotonin and acetylcholine transmitter systems are critical for a variety of brain functions such as mood regulation, learning, reinforcement of behavior, and nociception^{23, 52, 53}. We previously reported that the proximal promoter upstream of the mouse and rat TPH2 gene were specifically active in serotonergic neurons in mice and rats^{23, 41, 54}. However, no selective promoter for primate serotonergic and cholinergic neurons has been reported. We identified conserved promoter region of the upstream of the serotonin transporter (SERT) gene (Fig. 4A). Two LVVs containing conserved promoter regions (LVV-SERT-0.5 kb::Venus and LVV-SERT-1.9 kb::Venus) were constructed and injected into the dorsal raphe nucleus, the largest serotonergic nucleus. Immunohistochemical

analysis revealed specific GFP expression in animals injected with the longer promoter (colocalization rate $93.8 \pm 0.9 \%$, $n = 3$ mice; Fig. 4D, E), whereas the shorter was non-selective (colocalization rate $56.3 \pm 1.4 \%$, $n = 3$ mice; Fig. 4B, C). Similarly, we identified conserved promoter region upstream of the vesicular acetylcholine transporter (vAChT) gene, which is a marker of cholinergic neurons⁵⁵. Two LVVs containing conserved promoter regions (LVV-vAChT-1.1 kb::Venus and LVV-vAChT-1.8 kb::Venus) were tested in the latero-dorsal tegmental nucleus (LDTg). Similar to the result with the SERT promoters, the shorter promoter was less specific (colocalization with choline acetyl transferase, ChAT, at rate $52.3 \pm 4.8 \%$ $n = 3$ mice; Fig. 5B, C), while the longer promoter induced more specific GFP expression (colocalization rate $83.1 \pm 3.9 \%$ $n = 3$ mice; Fig. 5D, E).

Moreover, we determined whether these promoters are sufficiently strong for inducing detectable level of fluorescence of Venus. We found that Venus fluorescence induced by LVV-SERT-1.9kb::Venus was not detectable without immunohistochemical enhancement (Supplementary Fig. S1D), whereas that induced by LVV-vAChT-1.8kb::Venus was barely detectable (Supplementary Fig. S1E).

Isolation and functional validation of promoter candidates for striatal medium spiny neurons

The striatum is anatomically a part of the basal ganglia and plays a key role in motor function as well as decision making⁵⁶⁻⁵⁸. A large population of striatal neurons are medium spiny neurons (MSNs), which project into the endopeduncular nucleus (internal globus

pallidus), external globus pallidus, and substantia nigra pars reticulata⁵⁶. There are two distinct clusters of MSNs; one expresses dopamine D1 receptors and substance P (SP) (D1-MSNs), and another expresses dopamine D2 receptors, adenosine A2A receptors and enkephalin (D2-MSNs). Previous reports have demonstrated that mouse promoters for SP and preproenkephalin (PENK) are specifically active in mouse D1-MSN and D2-MSN, respectively⁵⁹. Although previous reports used relatively long sequences containing distal upstream region and part of coding region, we used conserved promoter region upstream of the SP and PENK genes which did not contain any coding region for minimizing the promoter length (Fig. 6A, 7A). Two LVVs containing conserved promoter regions upstream of the SP gene and more distal non-conserved region for comparison were created and injected to the mouse striatum. Immunohistochemical analysis revealed that both the longer and shorter promoters induced specific GFP expression in SP-positive neurons (LVV-SP-0.8 kb::Venus; colocalization rate $91.7 \pm 3.8 \%$, $n = 3$ mice, Fig. 6B, C, LVV-SP-1.7 kb::Venus; colocalization rate $87.4 \pm 4.9 \%$, $n = 3$ mice, Fig. 6D, E). Similarly, we designed two LVVs containing conserved promoter regions upstream of the PENK gene and injected them into the mouse striatum. We found that the longer promoter (LVV-PENK-2.2 kb::Venus) showed low specificity (colocalization rate $61.0 \pm 5.8 \%$, $n = 3$ mice; Fig. 7D, E), whereas the shorter promoter (LVV-PENK-0.9 kb::Venus) induced more specific GFP expression in PENK-immunoreactive neurons (colocalization rate $88.0 \pm 1.7 \%$, $n = 3$ mice; Fig. 7B, C).

Next, we examined whether these promoters induce strong transgene expression so that fluorescence of transgene Venus is detectable without immunohistochemical

enhancement. We found that strong Venus fluorescence was induced by LVV-SP-0.8kb::Venus or LVV-PENK-0.9kb::Venus (Supplementary Fig. S1F, G).

In silico prediction and comparison of transcription factor binding to identified promoters

Sequence-specific transcription factors (TFs) play an important role in regulating the expression of target genes by binding to transcriptional regulatory regions, such as promoters and enhancers⁶⁰. Thus, we hypothesized that different levels of promoter specificity could be due to different degrees of TF binding to the promoters. To address this issue, we utilized ConSite, an in silico prediction method for TF binding to promoter sequences⁴⁷. We analyzed the longer promoters for each target gene by ConSite and identified TF binding sites in these promoters. Then, we counted the occurrence of each TF in the whole sequences of the longer promoters, in the sequences specific to the longer promoters, and in the sequences common to both the longer and shorter promoters (Supplementary Table 3). We found a number of TFs bound only to the sequences specific to the longer promoters or to the sequences common to both the longer and shorter promoters. We specifically focused on the differences between long and short versions of CCK and SERT promoters. In case of CCK, the shorter version was much more specific than the longer one (Fig. 2). This suggested that TFs, which bind to the sequence common to both the longer and shorter promoters, may contribute to the specificity. We found that Broad-complex 1, HNF-1, MEF2, and Suppressor of Hairless (SU(h)) were predicted to bind to the sequences common to both the longer and shorter CCK promoters but not to

the sequences specific to the longer promoters (Supplementary Table 3). Interestingly, according to the *in situ* hybridization data available from the Allen Mouse Brain Atlas⁶¹, the Mef2c expression pattern in the cerebral cortex is very similar to the expression pattern of CCK but not to those of PV and SST (Supplementary Fig. S2), highlighting the possible involvement of this TF.

Discussion

Promoters which are able to specifically express transgenes in sub-populations of central neurons are highly valuable tools but still are in short supply. Here we searched for promoters which contain evolutionally conserved sequences suitable for targeting an array of important neuronal phenotypes, which are common between monkey and mouse. Our assumption is that the most important regulatory elements such as binding sites of critical transcriptional factors should be retained in both species. We successfully identified several macaque promoters which specifically drove gene expression in the homologous populations of neurons in the mouse brain. However, we cannot rule out the possibility that sequences other than conserved regions in the promoter may play a key role in the specificity of the promoter. Thus, further investigation using mutated conserved sequences or randomly selected sequences from the respective promoters is needed to clearly show the importance of conserved sequences. Moreover, by using in silico TF binding prediction, we found TFs which are likely to be important for the specificity of the identified promoters. Although our initial screening for obvious reason had to be performed in the mouse, there are good reasons to expect that their selectivity

1 will be preserved in other species such as macaque.

2 Recent advances in genetic tools including optogenetic, chemogenetic, and imaging
3 constructs have revolutionized the ability to manipulate and record neuronal activity as
4 well as analysis of synapse-level connectivity underlying brain function^{6-15, 62, 63}. However,
5 practical application of these tools often requires sufficiently high and specific expression
6 of these tools in defined populations of neurons. In this study, we showed that upstream
7 regions of SST, CCK, PV, SERT, vAChT, SP, and PENK genes in crab-eating macaque
8 are capable of directing specific expression in the relevant populations of murine neurons.

9 Although the identified promoters except for SERT and vAChT were sufficiently strong
10 for inducing detectable level of transgene Venus fluorescence,

whether expression of
11 various transgenes driven by newly identified promoters will be sufficiently high for
12 manipulation and recording of neuronal activity *in vivo* remains to be seen. However, the
13 utilization of Cre in combination with a Cre-dependent expression cassette^{12, 13, 64} can
14 dramatically enhance the expression level with preserving high cell-type specificity.

15 Therefore, it should be possible to combine cell-specific expression of Cre with Cre-
16 dependent viral vectors to achieve the level of expression required for cell-type specific
17 manipulation and recording of neuronal activity even in the monkey. Indeed, Stauffer et
18 al.³² have successfully transduced and manipulated monkey dopamine neurons using this
19 approach. In this study, we injected each LVV to the brain area where target neurons

20 predominantly exist. Therefore, we cannot fully rule out the possibility that this
21 population bias might lead to overestimation of the specificity of promoters.

22 Systematic analysis of promoter sequences also contributes to development of the

transgenic animals, which are widely used to gain insights into molecular mechanisms and potential therapies for a variety of diseases⁶⁵. Transgenic macaques were first reported in 2001⁶⁶, and later in 2008⁶⁷ and 2016⁶⁸. In contrast to the methods usually used in mice, these reports used retroviral or lentiviral vectors for transgene expression. Therefore, it is possible that the LVVs with the identified promoters may be also effective in establishing cell-type specific transgenic macaque. It is worth noting that also the transgenic common marmoset, another non-human primate, with germline transmission has been established by LVVs⁶⁹. Considering that marmosets reach sexual maturity at 12-18 months, use of macaque promoters identified in this study or those of marmoset in generation of transgenic animals will provide new insights into a variety of mental and neurodegenerative diseases in primate models which are the best available approximation of human pathology.

While in this study we used LVV for speedy gene expression, adeno-associated virus (AAV) is currently the most popular vector used in rodent studies⁷⁰⁻⁷². Similar to LVV, AAV provides stable and long-term gene expression in the targeted cells⁷³. However, standard AAV cannot package more than 5 kb, while LVV can accommodate up to 9 kb^{73, 74}. From this perspective, all of the identified promoters in this study were shorter than 2 kb which could be incorporated into AAV while leaving sufficient space for the transgenes. However, considering the episomal and concatemeric nature of AAV genomes⁷⁵, which might affect the specificity and/or expression level, their performance in the AAV backbones requires further investigation.

In conclusion, we have successfully identified promoter sequences in the macaque

1 genome which may act as cell specific promoters in an array of neuronal sub-types and
2 tested them in the mouse. We believe that these promoters will be useful for further
3 application of genetic tools in non-human primates in a cell-type specific manner.

4

5

6

Acknowledgement

We thank Drs. H. Miyoshi and A. Miyawaki (RIKEN, Japan) for providing pCSII-Venus-PRE.

Conflict of Interest

None

Funding

This work was partly supported by Grant-in-Aid for Scientific Research from JSPS (to K.N., H.S., T.N., and S. Kaneko), AMED (to K.N., K.I. and S. Kaneko), Top 100 Russian Academic Excellence Project at the Baltic Federal University (to S. Kasparov), and Research Grant from Research Foundation for Opto-Science and Technology, from Nakatani Foundation for advancement of measuring technologies in biomedical engineering, and from Takeda Science Foundation (to K.N.).

References

- 1 Selkoe DJ. Alzheimer's disease: genes, proteins, and therapy. *Physiol Rev* 2001;
81: 741–66.
- 2 Frith U, Castelli F, Frith C, Happe F. Autism, Asperger syndrome and brain
mechanisms for the attribution of mental states to animated shapes. *Brain* 2002; :
1839–1849.
- 3 Dauer W, Przedborski S. Parkinson's disease: mechanisms and models. *Neuron*
2003; **39**: 889–909.
- 4 Harrison PJ, Weinberger DR. Schizophrenia genes, gene expression, and
neuropathology: On the matter of their convergence. *Mol Psychiatry* 2005; **10**:
40–68.
- 5 Pittenger C, Duman RS. Stress, depression, and neuroplasticity: A convergence
of mechanisms. *Neuropsychopharmacology* 2008; **33**: 88–109.
- 6 Boyden ES, Zhang F, Bamberg E, Nagel G, Deisseroth K. Millisecond-timescale,
genetically targeted optical control of neural activity. *Nat Neurosci* 2005; **8**:
1263–8.
- 7 Meisenbock G. The Optogenetic Catechism. *Science (80-)* 2009; **326**: 395–399.
- 8 Wheeler MA, Smith CJ, Ottolini M, Barker BS, Purohit AM, Grippo RM *et al.*
Genetically targeted magnetic control of the nervous system. *Nat Neurosci* 2016;
19: 756–761.
- 9 Armbruster BN, Li X, Pausch MH, Herlitze S, Roth BL. Evolving the lock to fit
the key to create a family of G protein-coupled receptors potentially activated by an

- 1 inert ligand. *Proc Natl Acad Sci USA* 2007; **104**: 5163–5168.
- 2 10 Alexander GM, Rogan SC, Abbas AI, Armbruster BN, Pei Y, Allen JA *et al.*
- 3 Remote control of neuronal activity in transgenic mice expressing evolved G
- 4 protein-coupled receptors. *Neuron* 2009; **63**: 27–39.
- 5 11 Gradinaru V, Mogri M, Thompson KR, Henderson JM, Deisseroth K. Optical
- 6 deconstruction of parkinsonian neural circuitry. *Science (80-)* 2009; **324**: 354–9.
- 7 12 Lammel S, Lim BK, Ran C, Huang KW, Betley MJ, Tye KM *et al.* Input-specific
- 8 control of reward and aversion in the ventral tegmental area. *Nature* 2012; **491**:
- 9 212–217.
- 10 13 Tye KM, Mirzabekov JJ, Warden MR, Ferenczi EA, Tsai HC, Finkelstein J *et al.*
- 11 Dopamine neurons modulate neural encoding and expression of depression-
- 12 related behaviour. *Nature* 2013; **493**: 537–541.
- 13 14 Roth BL. DREADDs for Neuroscientists. *Neuron* 2016; **89**: 683–694.
- 14 15 Gomez JL, Bonaventura J, Lesniak W, Mathews WB, Sysa-Shah P, Rodriguez
- 15 LA *et al.* Chemogenetics revealed: DREADD occupancy and activation via
- 16 converted clozapine. *Science (80-)* 2017; **357**: 503–507.
- 17 17 Nakamura K, Matsumoto M, Hikosaka O. Reward-dependent modulation of
- 18 neuronal activity in the primate dorsal raphe nucleus. *J Neurosci* 2008; **28**: 5331–
- 19 43.
- 20 18 Isa T, Yamane I, Hamai M, Inagaki H. Japanese macaques as laboratory animals.
- 21 *Exp Anim* 2009; **58**: 451–457.
- 22 19 Knobloch HS, Charlet A, Hoffmann LC, Eliava M, Khrulev S, Cetin AH *et al.*

- 1 Evoked axonal oxytocin release in the central amygdala attenuates fear response.
2 *Neuron* 2012; **73**: 553–566.
- 3 20 Belzung C, Turiault M, Griebel G. Optogenetics to study the circuits of fear- and
4 depression-like behaviors: A critical analysis. *Pharmacol Biochem Behav* 2014;
5 **122**: 144–157.
- 6 21 Pelluru D, Konadhode RR, Bhat NR, Shiromani PJ. Optogenetic stimulation of
7 astrocytes in the posterior hypothalamus increases sleep at night in C57BL/6J
8 mice. *Eur J Neurosci* 2016; **43**: 1298–1306.
- 9 22 Gafford GM, Ressler KJ. Mouse models of fear-related disorders: Cell-type-
10 specific manipulations in amygdala. *Neuroscience* 2016; **321**: 108–120.
- 11 23 Nishitani N, Nagayasu K, Asaoka N, Yamashiro M, Andoh C, Nagai Y *et al.*
12 Manipulation of dorsal raphe serotonergic neurons modulates active coping to
13 inescapable stress and anxiety-related behaviors in mice and rats.
14 *Neuropsychopharmacology* 2019; **44**: 721–732.
- 15 24 Madisen L, Zwingman TA, Sunkin SM, Oh SW, Zariwala HA, Gu H *et al.* A
16 robust and high-throughput Cre reporting and characterization system for the
17 whole mouse brain. *Nat Neurosci* 2010; **13**: 133–40.
- 18 25 Madisen L, Mao T, Koch H, Zhuo JM, Berenyi A, Fujisawa S *et al.* A toolbox of
19 Cre-dependent optogenetic transgenic mice for light-induced activation and
20 silencing. *Nat Neurosci* 2012; **15**: 793–802.
- 21 26 Diester I, Kaufman MT, Mogri M, Pashaie R, Goo W, Yizhar O *et al.* An
22 optogenetic toolbox designed for primates. *Nat Neurosci* 2011; **14**: 387–97.

- 1 27 Jazayeri M, Lindbloom-Brown Z, Horwitz GD. Saccadic eye movements evoked
2 by optogenetic activation of primate V1. *Nat Neurosci* 2012; **15**: 1368–70.
- 3 28 Dai J, Brooks DI, Sheinberg DL. Optogenetic and electrical microstimulation
4 systematically bias visuospatial choice in primates. *Curr Biol* 2014; **24**: 63–69.
- 5 29 Watakabe A, Ohtsuka M, Kinoshita M, Takaji M, Isa K, Mizukami H *et al.*
6 Comparative analyses of adeno-associated viral vector serotypes 1, 2, 5, 8 and 9
7 in marmoset, mouse and macaque cerebral cortex. *Neurosci Res* 2015; **93**: 144–
8 157.
- 9 30 Nassi JJ, Avery MC, Cetin AH, Roe AW, Reynolds JH. Optogenetic Activation
10 of Normalization in Alert Macaque Visual Cortex. *Neuron* 2015; **86**: 1504–1517.
- 11 31 Klein C, Evrard HCC, Shapcott KAA, Haverkamp S, Logothetis NKK, Schmid
12 MCC. Cell-Targeted Optogenetics and Electrical Microstimulation Reveal the
13 Primate Koniocellular Projection to Supra-granular Visual Cortex. *Neuron* 2016;
14 **90**: 143–151.
- 15 32 Stauffer WR, Lak A, Yang A, Borel M, Paulsen O, Boyden ES *et al.* Dopamine
16 Neuron-Specific Optogenetic Stimulation in Rhesus Macaques. *Cell* 2016; **166**:
17 1564–1571.e6.
- 18 33 El-Shamayleh Y, Kojima Y, Soetedjo R, Horwitz GD. Selective Optogenetic
19 Control of Purkinje Cells in Monkey Cerebellum. *Neuron* 2017; **95**: 51–62.e4.
- 20 34 Dermitzakis ET, Clark AG. Evolution of transcription factor binding sites in
21 Mammalian gene regulatory regions: conservation and turnover. *Mol Biol Evol*
22 2002; **19**: 1114–21.

- 1 35 Xie X, Lu J, Kulbokas EJ, Golub TR, Mootha V, Lindblad-toh K *et al.*
2 Systematic discovery of regulatory motifs in human promoters and 3'UTRs by
3 comparison of several mammals. *Nature* 2005; **434**: 338–345.
- 4 36 Urban-Ciecko J, Barth AL. Somatostatin-expressing neurons in cortical
5 networks. *Nat Rev Neurosci* 2016; **17**: 401–409.
- 6 37 Freund TF. Interneuron Diversity series: Rhythm and mood in perisomatic
7 inhibition. *Trends Neurosci* 2003; **26**: 489–495.
- 8 38 Wang H-L, Morales M. Pedunculopontine and laterodorsal tegmental nuclei
9 contain distinct populations of cholinergic, glutamatergic and GABAergic
10 neurons in the rat. *Eur J Neurosci* 2009; **29**: 340–358.
- 11 39 Descarries L, Watkins KC, Garcia S, Beaudet A. The serotonin neurons in
12 nucleus raphe dorsalis of adult rat: A light and electron microscope
13 radioautographic study. *J Comp Neurol* 1982; **207**: 239–254.
- 14 40 Saunders A, Macosko EZ, Wysoker A, Goldman M, Krienen FM, de Rivera H et
15 al. Molecular Diversity and Specializations among the Cells of the Adult Mouse
16 Brain. *Cell* 2018; **174**: 1015-1030.e16.
- 17 41 Benzekhroufa K, Liu BH, Teschemacher AG, Kasparov S. Targeting central
18 serotonergic neurons with lentiviral vectors based on a transcriptional
19 amplification strategy. *Gene Ther* 2009; **16**: 681–688.
- 20 42 Nagai T, Ibata K, Park ES, Kubota M, Mikoshiba K, Miyawaki A. A variant of
21 YFP with fast and efficient maturation for cell-biological applications. *Nature*
22 2002; **20**: 1585–1588.

- 1 43 Liu B, Paton JF, Kasparov S. Viral vectors based on bidirectional cell-specific
2 mammalian promoters and transcriptional amplification strategy for use in vitro
3 and in vivo. *BMC Biotechnol* 2008; **8**: 1–8.
- 4 44 Takahashi A, Nagayasu K, Nishitani N, Kaneko S, Koide T. Control of intermale
5 aggression by medial prefrontal cortex activation in the mouse. *PLoS One* 2014;
6 **9**: e94657.
- 7 45 Coleman JE, Huentelman MJ, Kasparov S, Metcalfe BL, Paton JFR, Katovich
8 MJ et al. Efficient large-scale production and concentration of HIV-1-based
9 lentiviral vectors for use in vivo. *Physiol Genomics* 2003; **12**: 221–8.
- 10 46 Franklin KBJ, Paxinos G (eds). The Mouse Brain in Stereotaxic Coordinates
11 Third Edition. (Academic Press, New York, 2007)
- 12 47 Sandelin A, Wasserman WW, Lenhard B. ConSite: web-based prediction of
13 regulatory elements using cross-species comparison. *Nucleic Acids Res* 2004; **32**:
14 W249-52.
- 15 48 Dittgen T, Nimmerjahn A, Komai S, Licznarski P, Waters J, Margrie TW *et al.*
16 Lentivirus-based genetic manipulations of cortical neurons and their optical and
17 electrophysiological monitoring in vivo. *Proc Natl Acad Sci U S A* 2004; **101**:
18 18206–11.
- 19 49 Yaguchi M, Ohashi Y, Tsubota T, Sato A, Koyano KW, Wang N *et al.*
20 Characterization of the Properties of Seven Promoters in the Motor Cortex of
21 Rats and Monkeys After Lentiviral Vector-Mediated Gene Transfer. *Hum Gene*
22 *Ther Methods* 2013; **24**: 333–344.

- 1 50 Dimidschstein J, Chen Q, Tremblay R, Rogers SL, Saldi GA, Guo L *et al.* A viral
2 strategy for targeting and manipulating interneurons across vertebrate species.
3 *Nat Neurosci* 2016; **19**: 1743–1749.
- 4 51 Ovcharenko I, Loots GG, Hardison RC, Miller W, Stubbs L. zPicture: Dynamic
5 alignment and visualization tool for analyzing conservation profiles. *Genome Res*
6 2004; **14**: 472–477.
- 7 52 Lucki I. The spectrum of behaviors influenced by serotonin. *Biol Psychiatry*
8 1998; **44**: 151–162.
- 9 53 Picciotto MR, Higley MJ, Mineur YS. Acetylcholine as a neuromodulator:
10 cholinergic signaling shapes nervous system function and behavior. *Neuron*
11 2012; **76**: 116–129.
- 12 54 Liu B, Tang F, Kasparov S, Benzekhrufa K, Teschemacher AG. Adenoviral
13 vectors for highly selective gene expression in central serotonergic neurons
14 reveal quantal characteristics of serotonin release in the rat brain. *BMC*
15 *Biotechnol* 2009; **9**: 23.
- 16 55 Prado VF, Roy A, Kolisnyk B, Gros R, Prado MAM. Regulation of cholinergic
17 activity by the vesicular acetylcholine transporter. *Biochem J* 2013; **450**: 265–
18 274.
- 19 56 Albin RL, Young AB, Penney JB. The functional anatomy of basal ganglia
20 disorders. *Trends Neurosci* 1989; **12**: 366–75.
- 21 57 Balleine BW, Delgado MR, Hikosaka O. The Role of the Dorsal Striatum in
22 Reward and Decision-Making. *J Neurosci* 2007; **27**: 8161–8165.

- 1 58 Kravitz A V, Freeze BS, Parker PRL, Kay K, Thwin MT, Deisseroth K *et al.*
2 Regulation of parkinsonian motor behaviours by optogenetic control of basal
3 ganglia circuitry. *Nature* 2010; **466**: 622–6.
- 4 59 Hikida T, Kimura K, Wada N, Funabiki K, Nakanishi S. Article Distinct Roles of
5 Synaptic Transmission in Direct and Indirect Striatal Pathways to Reward and
6 Aversive Behavior. *Neuron* 2010; **66**: 896–907.
- 7 60 Fickett JW, Hatzigeorgiou AG. Eukaryotic promoter recognition. *Genome Res*
8 1997; **7**: 861–878.
- 9 61 Lein ES, Hawrylycz MJ, Ao N, Ayres M, Bensinger A, Bernard A *et al.*
10 Genome-wide atlas of gene expression in the adult mouse brain. *Nature* 2007;
11 **445**: 168–176.
- 12 62 Bock DD, Lee WA, Kerlin AM, Andermann ML, Hood G, Wetzel AW *et al.*
13 Network anatomy and in vivo physiology of visual cortical neurons. *Nature*
14 2011; **471**: 177–82.
- 15 63 Kim J, Zhao T, Petralia RS, Yu Y, Peng H, Myers E *et al.* MGRASP enables
16 mapping mammalian synaptic connectivity with light microscopy. *Nat Methods*
17 2012; **9**: 96–102.
- 18 64 Vrontou S, Wong AM, Rau KK, Koerber HR, Anderson DJ. Genetic
19 identification of C fibres that detect massage-like stroking of hairy skin in vivo.
20 *Nature* 2013; **493**: 669–673.
- 21 65 Harvey BK, Richie CT, Hoffer BJ, Airavaara M. Transgenic animal models of
22 neurodegeneration based on human genetic studies. *J Neural Transm* 2011; **118**:

- 1 27–45.
- 2 66 Chan AW, Chong KY, Martinovich C, Simerly C, Schatten G. Transgenic
3 monkeys produced by retroviral gene transfer into mature oocytes. *Science* 2001;
4 **291**: 309–12.
- 5 67 Yang SH, Cheng PH, Banta H, Piotrowska-Nitsche K, Yang JJ, Cheng ECH *et*
6 *al.* Towards a transgenic model of Huntington’s disease in a non-human primate.
7 *Nature* 2008; **453**: 921–924.
- 8 68 Zhang X-D, Sang X, Qiu Z, Yu X, Liu Z, Xiong Z-Q *et al.* Autism-like
9 behaviours and germline transmission in transgenic monkeys overexpressing
10 MeCP2. *Nature* 2016; **530**: 98–102.
- 11 69 Sasaki E, Suemizu H, Shimada A, Hanazawa K, Oiwa R, Kamioka M *et al.*
12 Generation of transgenic non-human primates with germline transmission.
13 *Nature* 2009; **459**: 523–527.
- 14 70 Samaranch L, Salegio EA, San Sebastian W, Kells AP, Foust KD, Bringas JR *et*
15 *al.* Adeno-Associated Virus Serotype 9 Transduction in the Central Nervous
16 System of Nonhuman Primates. *Hum Gene Ther* 2012; **23**: 382–389.
- 17 71 Lerchner W, Corgiat B, Minassian V Der, Saunders RC, Richmond BJ. Injection
18 parameters and virus dependent choice of promoters to improve neuron targeting
19 in the nonhuman primate brain. *Gene Ther* 2014; **21**: 233–241.
- 20 72 Oguchi M, Okajima M, Tanaka S, Koizumi M, Kikusui T, Ichihara N *et al.*
21 Double virus vector infection to the prefrontal network of the macaque brain.
22 *PLoS One* 2015; **10**: 1–15.

- 1 73 Lentz TB, Gray SJ, Samulski RJ. Viral vectors for gene delivery to the central
2 nervous system. *Neurobiol Dis* 2012; **48**: 179–188.
- 3 74 Wu Z, Yang H, Colosi P. Effect of genome size on AAV vector packaging. *Mol*
4 *Ther* 2010; **18**: 80–86.
- 5 75 Schnepf BC, Clark KR, Klemanski DL, Pacak CA, Johnson PR. Genetic Fate of
6 Recombinant Adeno-Associated Virus Vector Genomes in Muscle. *J Virol* 2003;
7 **77**: 3495–3504.
- 8

Figure legends

Figure 1. Functional validation of macaque SST promoters in mouse.

A (top) Sequence similarity of upstream regions between mouse and macaque. (bottom) Schematic representation of isolated promoters. **B** One week after injection of LVV-SST-0.3 kb::Venus, transgene expression was analyzed immunohistochemically. Scale bars = 200 μ m (low magnification), 20 μ m (high magnification). **C** Colocalization rate of SST and Venus. n = 4 mice.

Figure 2. Functional validation of macaque CCK promoters in mouse.

A (top) Sequence similarity of upstream regions between mouse and macaque. (bottom) Schematic representation of isolated promoters. **B, D** One week after injection of LVV-CCK-0.5 kb::Venus (**B**) or LVV-CCK-3.9 kb::Venus (**D**), transgene expression was analyzed immunohistochemically. Scale bars = 200 μ m (low magnification), 20 μ m (high magnification). **C, E** Colocalization rate of CCK and Venus after infection with LVV-CCK-0.5 kb::Venus (**C**) or LVV-CCK-3.9 kb::Venus (**E**). n = 3 mice.

Figure 3. Functional validation of macaque PV promoters in mouse.

A (top) Sequence similarity of upstream regions between mouse and macaque. (bottom) Schematic representation of isolated promoters. **B, D** One week after injection of LVV-PV-0.8 kb::Venus (**B**) or LVV-PV-1.8 kb::Venus (**D**), transgene expression was analyzed immunohistochemically. Scale bars = 200 μ m (low magnification), 20 μ m (high magnification). **C, E** Colocalization rate of PV and Venus after infection with LVV-PV-

0.8 kb::Venus (C) or LVV-PV-1.8 kb::Venus (E). n = 3 mice.

Figure 4. Functional validation of macaque SERT promoters in mouse.

A (top) Sequence similarity of upstream regions between mouse and macaque. (bottom) Schematic representation of isolated promoters. **B, D** One week after injection of LVV-SERT-0.5 kb::Venus (B) or LVV-SERT-1.9 kb::Venus (D), transgene expression was analyzed immunohistochemically. Scale bars = 200 μ m (low magnification), 20 μ m (high magnification). **C, E** Colocalization rate of TPH2, a marker for serotonin neurons, and Venus after infection with LVV-SERT-0.5 kb::Venus (C) or LVV-SERT-1.9 kb::Venus (E). n = 3 mice.

Figure 5. Functional validation of macaque vAChT promoters in mouse.

A (top) Sequence similarity of upstream regions between mouse and macaque. (bottom) Schematic representation of isolated promoters. **B, D** One week after injection of LVV-vAChT-1.1 kb::Venus (B) or LVV-vAChT-1.8 kb::Venus (D), transgene expression was analyzed immunohistochemically. Scale bars = 200 μ m (low magnification), 20 μ m (high magnification). **C, E** Colocalization rate of ChAT, a marker for acetylcholine neurons, and Venus after infection with LVV-vAChT-1.1 kb::Venus (C) or LVV-vAChT-1.8 kb::Venus (E). n = 3 mice.

Figure 6. Functional validation of macaque SP promoters in mouse.

A (top) Sequence similarity of upstream regions between mouse and macaque. (bottom)

1 Schematic representation of isolated promoters. **B, D** One week after injection of LVV-
2 SP-0.8 kb::Venus (B) or LVV-SP-1.7 kb::Venus (D), transgene expression was analyzed
3 immunohistochemically. Scale bars = 200 μ m (low magnification), 20 μ m (high
4 magnification). **C, E** Colocalization rate of SP and Venus after infection with LVV-SP-
5 0.8 kb::Venus (C) or LVV-SP-1.7kb::Venus (E). n = 3 mice.

6
7 **Figure 7. Functional validation of macaque PENK promoters in mouse.**

8 **A** (top) Sequence similarity of upstream regions between mouse and macaque. (bottom)
9 Schematic representation of isolated promoters. **B, D** One week after injection of LVV-
10 PENK-0.9 kb::Venus (B) or LVV-PENK-2.2 kb::Venus (D), transgene expression was
11 analyzed immunohistochemically. Scale bars = 200 μ m (low magnification), 20 μ m (high
12 magnification). **C, E** Colocalization rate of PENK and Venus after infection with LVV-
13 PENK-0.9 kb::Venus (C) or LVV-PENK-2.2kb::Venus (E). n = 3 mice.